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BRIEF REPORT

Target resolution in visual search involves the direct suppression of distractors: Evidence from electrophysiology

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Abstract

Attentional selection requires both the enhancement of target stimuli and the suppression of distractors. Target enhancement and distractor suppression have been associated with separable components of the lateralized event-related potential: the target negativity and distractor positivity (Pd). We examined the distractor suppression mechanisms indexed by the Pd. The Pd may reflect mechanisms that guide attention away from distractors during search or mechanisms involved in the subsequent resolution of target features. To determine which of these alternatives was more likely, we had participants view search arrays that contained only a target, only a distractor, or both. The Pd elicited by distractors was substantially larger when the display also contained a target, consistent with the idea that this component reflects a mechanism of distractor suppression activated during the resolution and disambiguation of target features.

In human electrophysiological research, selection of a visual search target in the presence of distractors has been associated with the N2pc component of the event-related potential (ERP), which begins at approximately 180 ms poststimulus—in the latency range of the N2—and distributes over posterior scalp contralateral to an attended object (Luck & Hillyard, 1994a, 1994b). In early investigations, Luck and colleagues linked the N2pc to distractor suppression processes that occur during target resolution (Luck & Ford, 1998; Luck, Girelli, McDermott, & Ford, 1997; Luck & Hillyard, 1994a, 1994b). They showed that an N2pc is not elicited when distractor suppression is counterproductive or impossible, as when search displays contain a target but no distractors, when the distractors provide critical information signaling the presence of the target, or when the distractors share task-relevant features with the target (Luck & Hillyard, 1994b).

However, not all N2pc results have supported the distractor suppression hypothesis. For example, Eimer (1996) demonstrated that a target can elicit an N2pc even when it is the only stimulus presented in one visual hemifield with all distractors in the contralateral hemifield, inconsistent with the intuition that an index of distractor suppression should be evident contralateral to distractors. Similarly, Shedden and Nordgaard (2001) found that a single stereoscopic figure elicited the N2pc in the absence of conventional distractor objects (see also Mazza, Turatto, & Caramazza, 2009).

On the basis of these and other results, Hickey, Di Lollo, and McDonald (2009) recently proposed that the N2pc might reflect the

operation of multiple, overlapping mechanisms, some acting on target representations and others acting on distractors. In their study, participants viewed search arrays containing one target and one distractor. In critical conditions, one of the two stimuli was presented on the vertical meridian and the other was lateralized. The idea was that the stimulus on the vertical meridian would be represented bilaterally, and thus would not contribute to a lateralized component like the N2pc. Lateralized activity could, therefore, be unambiguously associated with the lateralized stimulus. Lateralized targets evoked a contralateral negativity in the N2pc time window, whereas lateralized distractors evoked a contralateral positivity through the same interval. These results suggested that the N2pc can be decomposed into two overlapping subcomponents: the *target negativity* (Nt), which reflects modulation of target processing, and the *distractor positivity* (Pd), which reflects the suppression of distractors.

The current study examines two alternative interpretations of the Pd. First, it is possible that the component indexes mechanisms that suppress distractor features whenever they are present, as proposed by Sawaki and Luck (2010). Such a mechanism could guide attention during visual search, suppressing stimuli with known distractor features so that other, task-relevant stimuli could be detected and attended (Kaptein, Theeuwes, & Van der Heijden, 1995). If the Pd reflects this type of mechanism, the critical antecedent for the component should be the presence of a stimulus with known distractor features; the component should be evident even when no target is present in the display.

On the other hand, the Pd could reflect mechanisms recruited during target resolution. Competition-based models of vision suggest that the association of visual features to the target stimulus likely involves the suppression of distractor features (i.e., disam-

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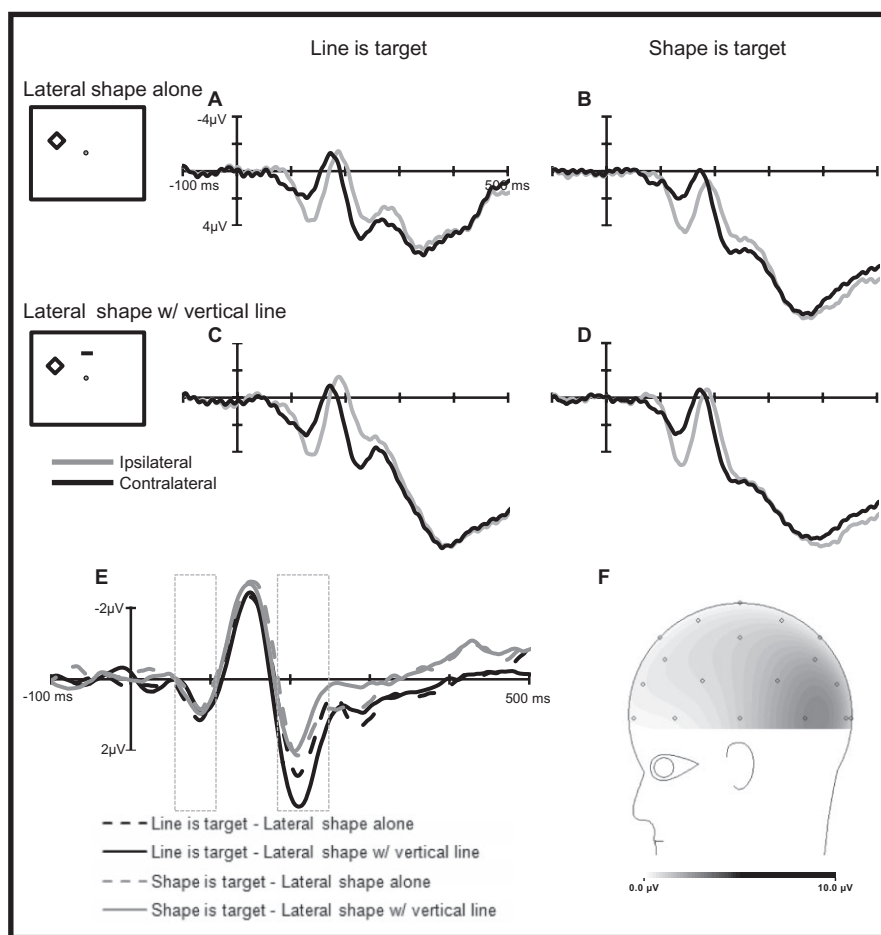


Figure 1. ERPs elicited by the lateralized green shape at electrodes PO3/4 as a function of target type and set size. Boxes indicate approximate analysis windows. A–D: Contralateral and ipsilateral waveforms. E: Contralateral minus ipsilateral difference waveforms. F: Scalp topography of the Pd component from the condition where the green shape distractor was presented concurrently with the red line target.

biguation; Desimone & Duncan, 1995; Luck et al., 1997). If a distractor is presented alone, there is no competition, and no suppression is necessary to disambiguate the neural representation. However, if the distractor is presented concurrently with a target, the Pd could index suppression of the distractor responsible for disambiguation of the target representation. In other words, the component should only be evident when a target is present in the display.

Method

Participants

Eighteen students participated for course credit, and 14 were included in the analysis (M age = 19.9 years, SD = 1.5 years, 5 women; see below for exclusion criteria). All research was approved by the Institutional Review Board at the Georgia Institute of Technology, and all participants gave informed consent.

Procedure

We used a procedure based on Experiment 4 of Hickey and colleagues (2009) with additional conditions in which the target or distractor appeared alone. Briefly, participants viewed visual search arrays that could contain a green shape ($0.6^\circ \times 0.6^\circ$) that

was a square or diamond, a horizontal red line that was long ($1.2^\circ \times 0.15^\circ$) or short ($0.8^\circ \times 0.15^\circ$), or both stimuli at different locations. Participants matched the background (M illuminance = 17.47 cd/m^2) to be isoluminant with the shade of red used to define the line stimulus (6.92 cd/m^2 ; see Hickey et al., 2009, for description of the luminance matching procedure). The shade of green used to define the shape stimulus (41.25 cd/m^2) was more luminous than the background. Stimuli could be presented to one of six screen locations (0° , 60° , 120° , 180° , 240° , and 300° off vertical), equidistant (5°) from a central fixation point and neighboring locations.

Four stimulus configurations were employed: the bright shape could be presented alone at a lateral location, the line could be presented alone at a lateral location, the shape and line could be presented together with the shape on the vertical meridian and the line at a lateral location, or the line and shape could be presented together with the line on the vertical meridian and the shape at a lateral location (see Figures 1 and 2 for examples). The stimulus locations were varied pseudorandomly from trial to trial such that the array always corresponded to one of the configurations. In each trial, the form of the shape and length of the line were randomized.

There were 32 blocks of 40 trials. Trials began with a fixation for 1350–1650 ms followed by the search array, and a new trial began following response or when 750 ms had passed. The line was

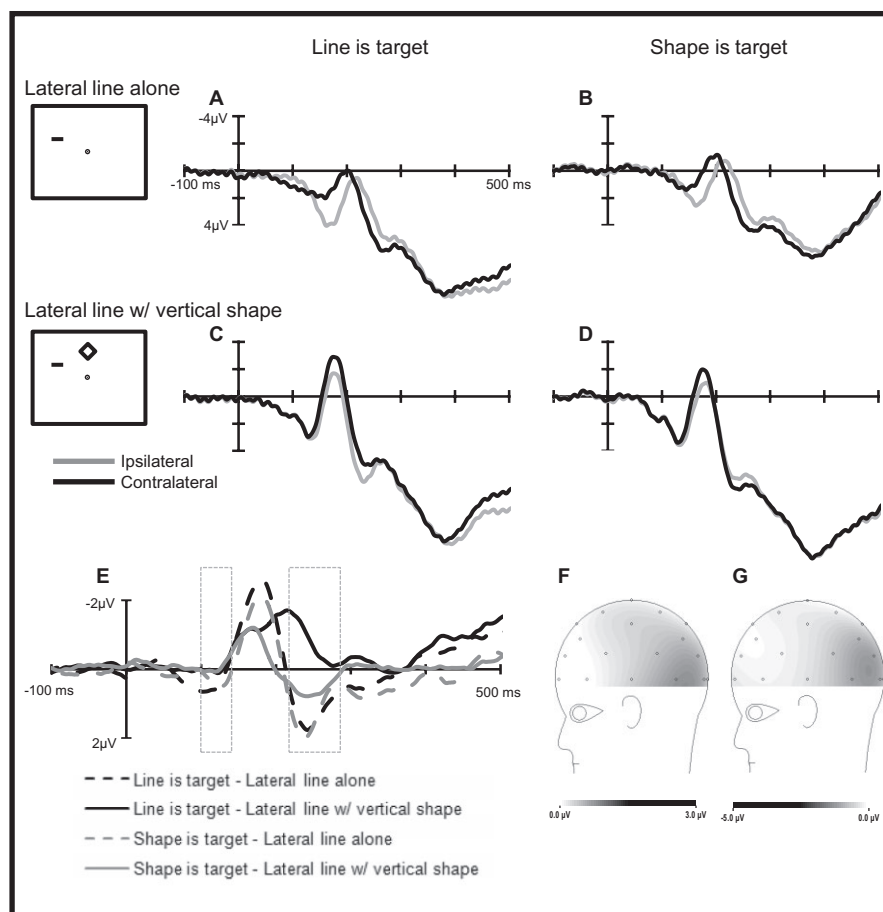


Figure 2. ERPs elicited by the lateralized red line at electrodes PO3/4 as a function of target type and set size. Boxes indicate approximate analysis windows. A–D: Contralateral and ipsilateral waveforms. E: Contralateral minus ipsilateral difference waveforms. F: Scalp topography of the Pd component from the condition where the red line distractor was presented concurrently with the green shape target. G: Scalp topography of the Nt component from the condition where the red line target was presented concurrently with the green shape distractor.

the target for half of all blocks, and the shape was the target for the remainder, and order of conditions was counterbalanced across participants. When the shape was the target, participants indicated whether it was a square or diamond. When the line was the target, participants indicated whether it was short or long. No response was required when the target was absent.

Behavioral Analysis

Percent errors (incorrect responses and misses) and reaction time were each assessed with a repeated-measures analysis of variance (RANOVA) with factors of target type (line vs. shape) and set size (one vs. two stimuli).

Electrophysiological Recording and Analysis

The electroencephalogram (EEG) was recorded from 32 scalp electrodes (FP1/FP2, AF3/4, FC1/2, FC5/6, F7/8, F3/4, Fz, C3/4, Cz, CP1/2, CP5/6, P7/8, PO3/4, P3/4, Pz, T7/8, O1/2, and Oz) using a Biosemi ActiveTwo amplifier system (Amsterdam, the Netherlands) and digitized at 512 Hz. Additional electrodes were positioned above and below the left eye, on the outer canthi of each eye, and on each mastoid.

EEG data were analyzed using BrainVision Analyzer (Brain Products, Gilching, Germany). Off-line, all scalp channels were

re-referenced to the algebraic average of the left and right mastoids. Electrooculogram (EOG) was calculated as the difference between electrodes positioned above and below the left eye, and on the outer canthi of each eye for vertical EOG (VEOG) and horizontal EOG (HEOG), respectively. Continuous EEG was digitally bandpass filtered from 0.1 to 30 Hz using a zero phase-shift Butterworth filter (12 dB/oct) and segmented into 900-ms segments beginning 200 ms before the stimulus. Segments were baseline corrected by subtracting the average signal recorded in the 200 ms before the stimulus. Segments containing activity greater than $\pm 80 \mu\text{V}$ in the scalp and VEOG channels were considered artifacts and rejected. Additionally, we used a two-step procedure to exclude eye movements. First, activity greater than $\pm 50 \mu\text{V}$ in the HEOG channel were considered artifacts and rejected. Next, participant averages were formed for right and left visual field targets separately. Participants were excluded if their average HEOG activity exceeded $\pm 5 \mu\text{V}$. Four participants were excluded from the analysis, and the grand average HEOG activity of the remaining participants did not exceed $\pm 2.2 \mu\text{V}$. This ensured that no systematic eye movements over 0.2° were included in the data (Lins, Picton, Berg, & Scherg, 1993). Finally, only trials with a correct behavioral response were included in the ERP analysis.

Participant averages were formed separately for the lateral red line and the lateral green shape conditions. The ERP components

were quantified from the contralateral and ipsilateral waveforms at electrodes P3/4, PO3/4, P7/8, and O1/2. These electrode sites were chosen based on the scalp topographies of the Pd and Nt components (see Figures 1 and 2).

Lateral green shape. For the lateral green shape condition, the bright green shape was always present in the display, and sensory activity created by this stimulus was roughly equivalent across all conditions (see Figure 1). To examine this explicitly, we investigated the lateralized activity in an early interval (70–110 ms), chosen based on the grand average of all lateral green shape conditions. In this interval, we conducted a RANOVA with the factors electrode (P3/4, PO3/4, P7/8, O1/2), target type (line target vs. shape target), set size (one vs. two stimuli), and hemisphere (contralateral vs. ipsilateral). We expected a main effect of hemisphere, indicating that a sensory imbalance was present, but that hemisphere should not interact with target type or set size, indicating that the sensory activity was equated across conditions. Given this result, we could then use a single RANOVA to examine the later time windows.

The interval of interest that should contain the Pd component (185–250 ms) was also examined with the factors electrode (P3/4, PO3/4, P7/8, O1/2), target type (line target vs. shape target), set size (one vs. two stimuli), and hemisphere (contralateral vs. ipsilateral). The critical test is the three-way interaction between hemisphere, set size, and target type (or the four-way interaction including electrode). This test would indicate whether the Pd is larger contralaterally when the green shape is a distractor and when there the target is also present.

Lateral red line. For the lateral red line condition, the presence of the green shape had a substantial impact on sensory evoked activity in the ERP (see Figure 2), which made comparison between conditions with and without the green shape problematic. Indeed, others have shown that isoluminant stimuli delay the peak latency of ERP components compared to nonisoluminant stimuli, and this difference is particularly noticeable in the ipsilateral waveforms (Wijers, Lange, Mulder, & Mulder, 1997). To examine this explicitly, we investigated the lateralized activity in an early interval (100–140 ms), again chosen based on the grand average of all lateral red line conditions. In this interval, we conducted a RANOVA with the factors electrode (P3/4, PO3/4, P7/8, O1/2), target type (line target vs. shape target), set size (one vs. two stimuli), and hemisphere (contralateral vs. ipsilateral). Critically, we expected a Hemisphere \times Set Size interaction, indicating that the sensory imbalance was different depending on whether the red line was presented alone or concurrently with the green shape stimulus. Given this result, we could then conduct separate RANOVAs for when the lateral red line was presented alone and for when the green shape was concurrently presented on the vertical meridian.

The interval of interest (215–280 ms) was also examined using separate RANOVAs for when the lateral red line was presented alone and for when the green shape was concurrently presented on the vertical meridian. Both RANOVAs had the factors target type (line target vs. shape target) and hemisphere (contralateral vs. ipsilateral). When both objects were presented together, we expected an Nt component when the red line was the target and a Pd component when the red line was the distractor, which would replicate the results of Hickey et al. (2009). This result would be evident in a Hemisphere \times Target Type interaction.

For all the RANOVAs, because the components of interest were defined as differences between contralateral and ipsilateral wave-

forms, only main effects of hemisphere and interactions with hemisphere are reported. In addition, all RANOVAs are Huynh–Feldt corrected where appropriate.

Results

Behavior

Participants made more errors (incorrect responses and misses) when the target and distractor were presented together ($M = 14.82\%$, $SD = 8.43\%$) compared to when the target was presented alone ($M = 13.53\%$, $SD = 7.77\%$). Accordingly, there was a main effect of set size, $F(1,13) = 8.04$, $p < .05$, $\eta_p^2 = .38$. The main effect of target type, $F(1,13) = 2.78$, $p < .12$, $\eta_p^2 = .18$, and the interaction between target type and set size, $F < 1$, were not statistically significant.

For reaction time, there was a main effect of target type, $F(1,13) = 9.95$, $p < .01$, $\eta_p^2 = .43$, and set size, $F(1,13) = 5.06$, $p < .05$, $\eta_p^2 = .28$. However, these were qualified by a significant interaction between target type and set size, $F(1,13) = 4.84$, $p < .05$, $\eta_p^2 = .27$. This interaction indicated that the effect of set size was greater when the red line was the target compared to when the green shape was the target. When the red line was the target, participants were slower when the green shape was concurrently presented ($M = 555.37$ ms, $SD = 31.74$ ms) compared to when the red line was alone ($M = 548.58$ ms, $SD = 35.17$ ms). On the other hand, the reaction time to respond to the green shape target was approximately the same when the red line was concurrently presented ($M = 529.33$ ms, $SD = 43.75$ ms) compared to when the green shape was presented alone ($M = 528.15$ ms, $SD = 43.80$ ms).

Event-Related Potentials

Lateral green shape

70–110 ms. There was a main effect of hemisphere, $F(1,13) = 14.61$, $p < .005$, $\eta_p^2 = .53$, indicating that a contralateral positivity occurred, which reflects the sensory imbalance in the displays. There was a Hemisphere \times Electrode interaction, $F(3,39) = 14.77$, $p < .001$, $\eta_p^2 = .53$, $\epsilon = 1$, indicating that this sensory imbalance was maximal at electrodes P7/8. Critically, none of the other interactions with hemisphere were significant (all $F_s < 2.38$, $p_s > .15$), indicating that the sensory imbalance was equivalent across conditions.

185–250 ms. There was a main effect of hemisphere, $F(1,13) = 31.12$, $p < .001$, $\eta_p^2 = .71$, indicating a contralateral positivity occurred during this interval. There was a Hemisphere \times Electrode interaction, $F(3,39) = 4.62$, $p < .005$, $\eta_p^2 = .26$, $\epsilon = 1.0$, indicating that this contralateral positivity was maximal at electrodes P7/8. There was a significant Hemisphere \times Target Type interaction, $F(1,13) = 19.22$, $p < .001$, $\eta_p^2 = .60$, which was qualified by a significant Hemisphere \times Target Type \times Electrode interaction, $F(3,39) = 5.91$, $p < .005$, $\eta_p^2 = .31$, $\epsilon = 1.0$, indicating the contralateral positivity was greatest at P7/8 when the lateral green shape was a distractor. In addition, there was a Hemisphere \times Set Size interaction, $F(1,13) = 7.64$, $p < .05$, $\eta_p^2 = .37$, indicating that the contralateral positivity was greatest when both the distractor and target were presented together. Critically, there was a Hemisphere \times Target Type \times Set Size interaction, $F(1,13) = 22.01$, $p < .001$, $\eta_p^2 = .63$, indicating that the contralateral positivity was greatest when the lateral green shape was the

distractor and presented concurrently with the red line target. The other interactions with hemisphere were not statistically significant (both $F_s < 1$).

To investigate the three-way interaction, we conducted paired-samples t tests to address our central question: Is the Pd component elicited by a distractor presented alone or only when there is distractor and a concurrent target present? First, we collapsed across electrode. Then, we calculated difference scores by subtracting the ipsilateral activity from the contralateral activity. Next, we assumed that the bright green shape produces a sensory imbalance that affects all conditions equally (which was supported empirically by our examination of the 70–110-ms interval). Thus, we defined the Pd as a contralateral positivity greater than that caused by the sensory imbalance. Given this, we compared the difference scores for when the shape was a distractor presented alone and when the shape was a distractor presented with the target to the difference score when the shape target was presented alone to determine which distractor condition(s) elicited a Pd component.

When the shape distractor was presented alone, there was no detectable Pd component. Accordingly, the comparison between the shape distractor alone and shape target alone conditions was not statistically significant, $t(13) = -1.65$, $p < .12$. In contrast, a Pd was evident when the shape distractor was presented concurrently with the line target. Thus, the comparison between the shape distractor presented concurrently with the target and shape target alone conditions was statistically significant, $t(13) = -4.59$, $p < .005$.

Lateral red line

100–140 ms. There was a marginally reliable main effect of hemisphere, $F(1,13) = 3.85$, $p < .07$, $\eta_p^2 = .23$, indicating a contralateral positivity occurred that reflects the sensory imbalance in the displays. There was a Hemisphere \times Electrode interaction, $F(3,39) = 10.89$, $p < .001$, $\eta_p^2 = .46$, $\epsilon = .91$, indicating that this sensory imbalance was maximal at electrodes P7/8. Critically, there was a statistically significant Hemisphere \times Set Size interaction, $F(1,13) = 16.50$, $p < .001$, $\eta_p^2 = .56$, indicating that the contralateral positivity was greater when the red line was presented alone compared to when it was presented concurrently with the green shape. Therefore, for the remaining intervals we examined the set size conditions separately. None of the other interactions with hemisphere were significant (all $F_s < 1.85$, $ps > .18$).

215–280 ms

Red line alone. There was a main effect of hemisphere, $F(1,13) = 28.17$, $p < .001$, $\eta_p^2 = .68$, indicating that a contralateral positivity occurred. None of the other interactions with hemisphere were significant (all $F_s < 1.02$, $ps > .39$).

Red line with green shape. There was a statistically significant Hemisphere \times Target Type interaction, $F(1,13) = 24.03$, $p < .001$, $\eta_p^2 = .65$, indicating that a contralateral negativity was evident when the red line was a target whereas a contralateral positivity was evident when the red line was a distractor. However, this was qualified by a three-way Hemisphere \times Electrode \times Target Type interaction, $F(3,39) = 10.21$, $p < .001$, $\eta_p^2 = .44$, $\epsilon = .97$, indicating that the maximum difference between the two conditions occurred at electrode PO3/4.

Discussion

The results are consistent with the idea that the Pd reflects a suppressive mechanism recruited during the resolution of target information. For the lateralized green shape conditions, a contralateral positivity was evident in every condition (see Figure 1). We believe that much of this contralateral positivity reflects lateralized sensory activity due to the bright shape. In confirmation of this, there was a contralateral positivity evident in the early interval (70–100 ms) that did not vary by condition. This result demonstrates that a sensory imbalance occurred but that it was similar across conditions. However, in the interval of interest (185–250 ms), this contralateral positivity was substantially larger when the shape was a distractor and the line target was concurrently presented (Figure 1). We interpret this increase in the contralateral positivity as a Pd component superimposed on this underlying sensory activity. Therefore, the Pd component was only detectable when the target and distractor were presented concurrently. In this condition, there is competition between the target and distractor for representation in visual cortex. The Pd component may index mechanisms that suppress distractor features, and these mechanisms may be an important aspect in resolving the competition for representation between the target and distractor objects.

For the lateralized red line conditions, the line elicited a Pd when the shape target was presented on the vertical meridian and the line was a distractor, but these same displays elicited an Nt when the line was a target (Figure 2). In other words, when the target and distractor appeared together, there was clear evidence for an Nt and Pd component depending on whether the lateralized object was a target or distractor. This result is a direct replication of the result of Hickey and colleagues (2009), who were the first to demonstrate that the N2pc could be decomposed into an Nt and Pd component using the exact same displays as we used in this particular condition. Our results are consistent with Hickey and colleagues' interpretation of the Nt component such that it likely indexes processing of target features. In addition, our results indicate that the Pd component likely indexes the suppression of distractor features in aid of target resolution. When the line was presented alone in the lateralized red line conditions, a biphasic response can be seen in the difference waveforms that were attributable to a delay in the peak latency of the ipsilateral waveforms compared to the contralateral waveforms (Figure 2; cf. Wijers et al., 1997). Critically, this biphasic response did not vary depending on whether the line was a target or distractor. Thus, when the target or distractor appeared alone, we were not able to detect an Nt or Pd component.

To conclude, the current results demonstrate that the distractor-elicited Pd is only evident when a target is present in the display, consistent with the idea that this component reflects the operation of a suppressive mechanism recruited during target resolution. Thus, whereas other mechanisms of distractor suppression may certainly operate during attentional selection, we believe that the Pd indexes a mechanism that acts to disambiguate target features, consistent with competition-based models of visual attention (e.g., Desimone & Duncan, 1995; Luck et al., 1997).

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